Space VLBI Telecommunication Characteristics, Protection Criteria, and Frequency Sharing

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A brief description of the technical characteristics of space VLBI is made, emphasizing the VLBI cross-correlation process. The signal-to-noise ratio of the cross-correlation process should be maintained as large as possible for the duration of the observation. Protection of this process from unwanted interference is a primary objective. The telecommunication radio links required in a space VLBI system are identified and characterized. Maximum bandwidths are suggested, as well as the minimum carrier frequencies required for the telemetering and the phase-transfer radio links. Planned space VLBI system models—Radioastron (Russia), VLBI Space Observatory Project (VSOP) (Japan), and the DSN orbiting VLBI subnet (United States)—are taken as a baseline to determine the interference criteria. It is concluded that existing interference criteria for near-Earth research satellites are suitable for the protection of the space VLBI systems planned.

I. Introduction

Very long baseline interferometry (VLBI) is a technique that allows experimenters to achieve angular resolution of observed radio sources that cannot be approached by other radio or optical methods. VLBI has a wide variety of scientific and engineering uses [1,2]. Observations of distant radio sources with two or more VLBI stations are combined to determine the structure of extragalactic radio sources, determine geodynamical characteristics of the Earth, study the Moon's libration and tidal response, determine orientation of the solar system with respect to the extragalactic inertial frame, determine vector separation between antenna sites, and provide navigation and tracking of spacecraft.

II. Technical Characteristics

The operating approach of the most simple VLBI system, composed of two VLBI Earth stations, may be summarized as follows. The VLBI Earth antennas will point to the radio source, common to both antennas, for the planned experiment. Because of engineering limitations, the resulting observed frequency spectrum is usually translated down to a lower frequency. The amplitude and phase characteristics of this observed spectrum are maintained by using a highly stable reference frequency, a local oscillator (LO). The observed spectrum at each antenna is recorded independently in some supported medium (e.g., magnetic tape). In the case of space VLBI, one of the antennas used for the radio source observation is space borne, and the downconverted spectrum is transmitted and recorded at a space VLBI Earth station (Fig. 1).

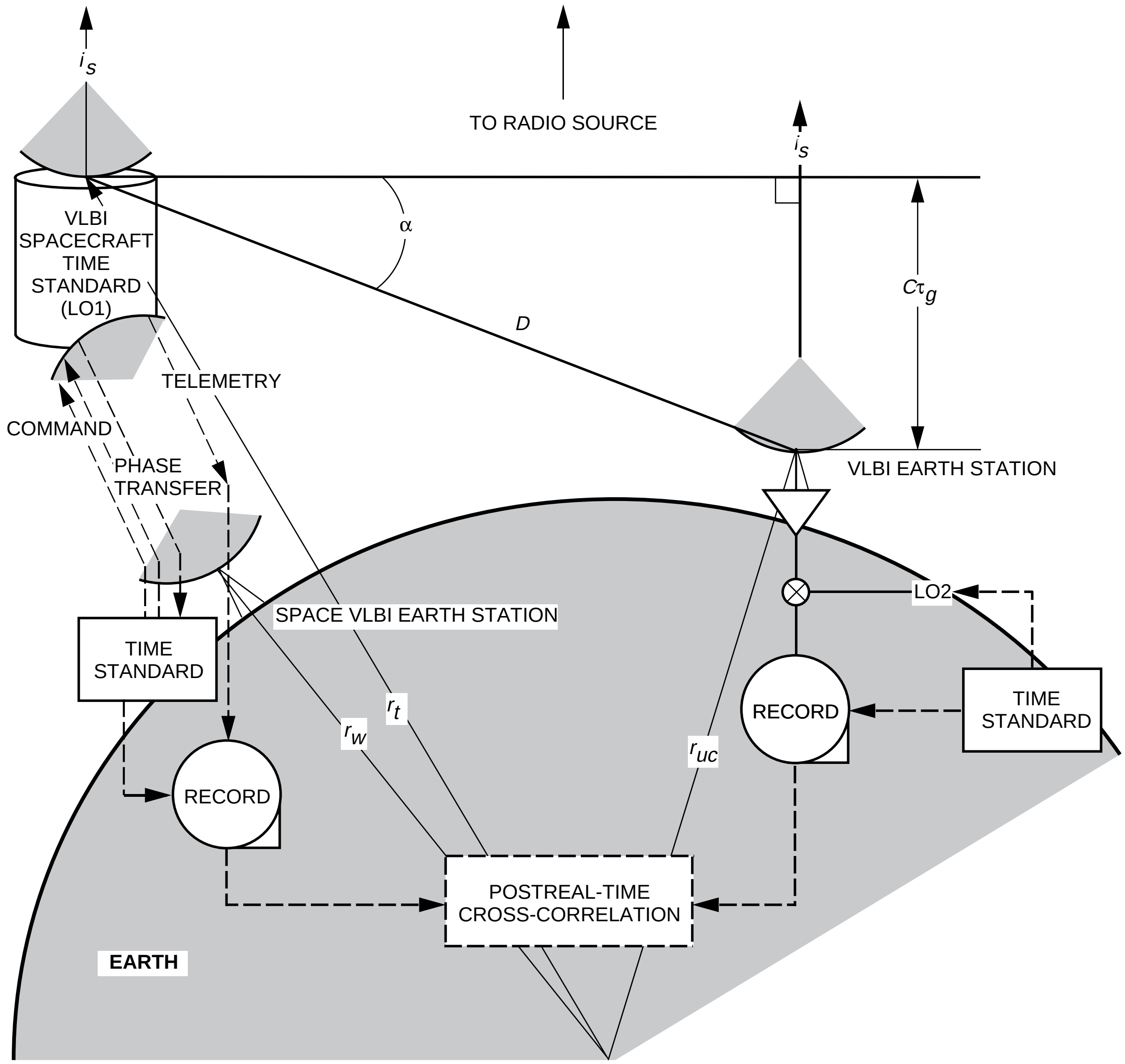

Fig. 1. Space VLBI geometry.

The basic observables in radio interferometry are the amplitude and relative phase of the cross-correlation of the two observed spectra. This cross-correlation process usually is performed in nonreal time and may be expressed as

$$R_{xy}(\tau_g) = \langle x(t)y(t-\tau_g)\rangle \tag{1}$$

where

$R_{xy} =$ cross-correlation function

$\langle\rangle =$ estimated mean for the observation period

$$x(t) = \text{recorded signal at site 1}$$

$$y(t) = \text{recorded signal at site 2}$$

$$\tau_g = \text{wave front time delay}$$

In the cross-correlation function of Eq. (1), the prerecorded signals will be contaminated with noise from the receiving systems. It has been shown that the cross-correlation signal-to-noise ratio, SNR_{cros}, may be expressed as a function of the two observing signal-to-noise ratios, SNR_{obs1} and SNR_{obs2}, as

$$SNR_{cros} = (SNR_{obs1} SNR_{obs2} BT)^{1/2} \tag{2}$$

where B is the observing bandwidth and T is the integration time of each observation. The SNR_{cros} should be maintained as large as possible to decrease the error in the τ_g measurement in Eq. (1).

The sensitivity (signal-to-noise ratio = 1) of this two-element VLBI interferometer may be determined [3]:[1]

$$S_d = 4(2)^{1/2} 10^{26} k (T_1 T_2)^{1/2} (\pi g D_1 D_2)^{-1} (\eta_1 \eta_2)^{-1/2} (BT)^{-1/2} \text{ (Janskys)} \tag{3}$$

where

$$k = \text{Boltzmann's constant} = 1.38 \times 10^{-23} \text{ (W/K-Hz)}$$

$$T_1, T_2 = \text{system temperatures}$$

$$D_1, D_2 = \text{antenna diameters}$$

$$\eta_1, \eta_2 = \text{antenna aperture efficiencies}$$

$$g = \text{coherence of the VLBI system}$$

$$T = \text{integration time}$$

$$B = \text{noise bandwidth}$$

This is equivalent to the root-mean-square (rms) noise divided by the coherence, g.

In VLBI, a "quasi-common" time reference frame at both observing stations is essential because of the need for precise knowledge of the signal frequency and phase. Also, precise time information is needed for the postreal-time cross-correlation. These requirements are met with high-stability oscillators often referred to as "atomic clocks." It is desirable to provide the space VLBI spacecraft with a space-qualified atomic clock in the future. For the time being, an Earth-to-space (E–S) phase-transfer radio link will be needed to impart the required timing or phase reference to the spacecraft's onboard clock.

A. Telecommunication Links for Space VLBI

The telecommunication radio links to be considered in a space VLBI system are represented in Fig. 1 by the four dashed lines between the space VLBI spacecraft telecommunication antenna and the space VLBI Earth station. A description of the radio links follows.

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[1] J. Ulvestad, R. Freeland, G. Levy, D. Meier, D. Murphy, and R. Preston, "Future Space VLBI Options," draft midyear report (internal document), Jet Propulsion Laboratory, Pasadena, California, May 4, 1992.

1. E–S Telecommand Radio Link. This radio link is used for reliable transmission of telecommands required for operation and correction of possible malfunctions of spacecraft behavior.

2. E–S Phase-Transfer Radio Link. The main use of this link will be for translation to the spacecraft of the phase and frequency stability of the atomic clock located at the space VLBI Earth station. This high stability is needed for the duration of the observation time and should be of the same order of magnitude as the one in the atomic clock at the space VLBI Earth station.

3. Space-to-Earth (S–E) Telemetering Radio Link. The space VLBI spacecraft observes the radio source over a selected bandwidth. This observed spectrum is transmitted to the space VLBI Earth station for recording and future cross-correlation with the observed spectrum from one or more VLBI Earth stations.

4. S–E Phase-Transfer Radio Link. This radio link will be a coherent frequency translation of the E–S phase-transfer radio link described above and will be used to calibrate the phase errors introduced in the E–S phase-transfer radio link by various causes. This radio link may be dedicated to this phase-transfer operation or may simultaneously be used to transfer the observing spectra from the spacecraft, as described in Section II.A.3.

B. Telemetering Link Characterization

The space VLBI spacecraft receives the radio source frequency spectrum contaminated with noise (background, system, etc.) in a selected observing bandwidth, B, at a given observing SNR, SNR_{obs1}. This observed spectrum has to be transmitted to the space VLBI Earth station to be recorded and further processed (cross-correlated). This transmission may be an analog transmission or the observed analog signal may be converted to a digital format and transmitted to the space VLBI Earth station for recording.

The transmission through space of a telemetry signal implies some signal degradation when detected at the intended receiver. In digital transmissions, this degradation is due to the probability of information bits being in error and is dependent on the received symbol signal-to-noise ratio (SSNR). This link degradation will affect the final process of the space VLBI experiment, i.e., the cross-correlation function in Eq. (1). Figure 2 shows typical results of the $\mathrm{SNR_{cros}}$ degradation [Eq. (2)] as a function of the space VLBI Earth station telemetering link performance. Results for analog, 1-bit, and 2-bit binary representations have been included. Note the inherent degradation introduced by the digital conversion. This degradation is a function of the quantization levels utilized in the analog-to-digital conversion.

1. Required Telemetering Channel Bandwidth. Phase modulation has been shown to attain optimum performance on satellite telecommunications links. Therefore, binary phase shift keying (BPSK) or quadriphase shift keying (QPSK) will be considered the preferred digital modulation schemes.

When digitizing the observing bandwidth of B Hz, the required Nyquist sampling rate will be twice the bandwidth, or $2B$ samples per sec. Each observed voltage sample is quantized at either two levels (1-bit representation), four levels (2-bit representation), or eight levels (3-bit representation), etc. The total telemetering channel symbol rate required will, therefore, follow

$$SR = 2B \ \log_2 (L) \tag{4}$$

with

$SR =$ total data rate (symbols/sec)

$B =$ observed bandwidth (Hz)

$L =$ total number of quantization levels

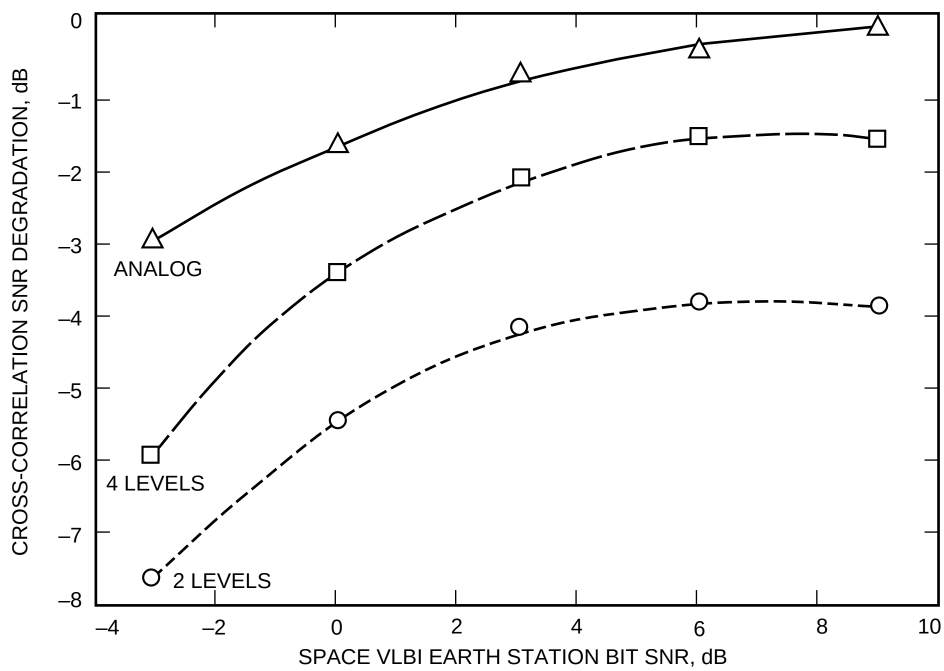

Fig. 2. Cross-correlation SNR degradation as a function of binary representation and telemetry SNR.

The radio frequency bandwidth, BW, required for the transmission of BPSK (telemetry losses less than 0.3 dB) has been recommended by the International Radio Consultative Committee (CCIR) as

$$BW = 5SR \tag{5}$$

If QPSK is used, the same bandwidth can accommodate twice the symbol rate with approximately the same performance as the BPSK case. Table 1 presents a summary of all the above considerations, showing the required radio frequency (RF) bandwidths as a function of observation bandwidth, B. Note that smaller bandwidths than those recommended may be used at a cost of link performance.

Planned space VLBI systems (see Table 2) typically use data rates on the order of 72 megasymbols/sec and QPSK modulation.[2] The maximum RF bandwidth required would, therefore, be on the order of 360 MHz (from Table 1). Theoretical studies of propagation effects on wide bandwidth transmissions have indicated that the atmosphere can support several gigahertz of bandwidth at carrier frequencies above 10 GHz. Therefore, transmission bandwidths on the order of 3–4 GHz may very well be envisioned for future VLBI systems.

2. Required S–E Telemetering Carrier Frequencies. Planned space VLBI systems with maximum RF transmission bandwidth requirements of less than 500 MHz will be very well allocated at carrier frequencies larger than 3 GHz. Future RF bandwidth requirements (4 GHz) indicate the need for carrier frequencies larger than 20 GHz.

C. Phase-Transfer Link Characterization

A prime requirement of a space VLBI spacecraft's onboard clock is that its frequency/phase stability be nearly as good as that of a VLBI Earth station's atomic clock. No space-qualified atomic clocks

[2] J. Ovnick, "Design Requirements for DSN Orbiting VLBI Subnet," DM515606A, Rev. A (internal document), Jet Propulsion Laboratory, Pasadena, California, March 31, 1992.

exist today; therefore, the required stability will be transferred to the space VLBI spacecraft via an E–S radio link. The carrier frequency of this radio link, f_{up}, is recovered at the spacecraft to generate the onboard reference frequencies to be used in the radio source observing process. In order to calibrate all the unknown phase errors introduced in this E–S phase-transfer radio link, this carrier frequency is coherently downconverted and transmitted back to the space VLBI Earth station, f_{down}. In this two-way phase calibration transfer system, phase errors are mainly introduced by the propagation medium and the receiving systems (spacecraft and space VLBI Earth station). These phase errors will contribute to the uncertainty in the determination of the amplitude and relative phase of the nonreal-time cross-correlation process of Eq. (1), effectively lowering the SNR_{cros} of Eq. (2).

Table 1. Required radio frequency bandwidth.

Signal presentation	Quantization levels	Bits, number	Symbol rate, symbols/sec	RF bandwidth, Hz		
				Analog	BPSK	QPSK
Analog	—	—	—	$2B$ (minimum)	—	—
[0,1]	2	1	$2B$	—	$10B$	$5B$
[00,01,10,11]	4	2	$4B$	—	$20B$	$10B$
[000,001,010,011,100,101,110,111]	8	3	$6B$	—	$30B$	$15B$

Table 2. Characteristics of planned space VLBI systems.

Parameter	Radioastron	VSOP	IVS
Observing antenna diameter, m	10	10	20
Observing frequency and system temperature, GHz; K	0.3; 90	1.6; 40	4.5; 8.5
	1.6; 60	5.0; 60	15; 23
	5.0; 70	22.0; 110	42; 63
	22.0; 135	—	86; 120
Nominal integration time, sec	300	300	—
Space-to-Earth			
Frequency, GHz	14–15.35	14–15.35	—
Modulation type	QPSK	QPSK	—
Maximum bit rate, MB/sec	144	128	—
Quantization, levels	2, 4	2, 4	—
RF bandwidth, MHz	500	500	—
Minimum E_b/N_o, dB	11.2	9.1	—
Earth-to-space (phase transfer)			
Frequency, GHz	7.145–7.235	15.25–15.35	—
Modulation type	None	None	—
Maximum bit rate, MB/sec	—	—	—
RF bandwidth, MHz	50	100	—
PLL bandwidth, Hz	1000	1000	—
Minimum P_c/N_o, dB/Hz	63	60	—
Orbital characteristics			
Inclination, deg	51.5–65.0	31	63
Height at perigee, km	2000	1000	5000
Height at apogee, km	78,980	20,000	150,000
Period, hr	28	6.06	67.14

1. Radio Frequency Propagation-Induced Phase Noise. The phase, ϕ_{up}, of the onboard reference frequency, f_{up}, is retrieved from the measured round-trip phase, ϕ_{round}, measured at the ground station through the following:

$$\phi_{up} = \frac{f_{up}}{f_{up} + f_{down}}\ \phi_{round} \tag{6}$$

There exists frequency-dependent path delay, τ_i, in the propagation of an electromagnetic wave through the ionosphere. Therefore, Eq. (6) should be modified to

$$\phi_{up} = \frac{f_{up}}{f_{up} + f_{down}}\ \phi_{round} + 2\pi\ \frac{f_{up} f_{down}}{f_{up} + f_{down}}\ [\tau_i(f_{up}) - \tau_i(f_{down})] \tag{7}$$

with

$$\tau_i(f) = \frac{40.3}{cf^2}\ TEC_i\ (\text{sec})$$

with

$$\begin{aligned} c &= \text{velocity of light (m/sec)} \\ f &= \text{propagation frequency (Hz)} \\ TEC_i &= \text{total electron content (electrons/m}^2\text{)} \end{aligned}$$

The second term in the right side of Eq. (7) is an error term due to a frequency-dependent ionospheric delay. Unless additional information about the total electron content, TEC_i, in the ionosphere is provided, a proper correction for this error cannot be made. Nevertheless, this error becomes smaller if frequencies of both f_{up} and f_{down} are made higher and closer to each other. Table 3 gives the calculated results of this error in units of picosecond (psec) time delay, i.e., $\phi_{up}/2\pi f_{up}$, for two frequency pairs (7.2–8.46 GHz and 15.3–14.2 GHz). A total electron content of 8×10^{17} electrons/m^2 has been assumed.

Table 3. Ionospheric propagation effects.

Link frequencies, GHz		Absolute value of ionospheric error, psec (for $TEC = 8 \times 10^{17}$ electrons/m^2)	Coherence factor scintillation index, S	
F_{up}	F_{down}		$S = 0.1$	$S = 0.5$
7.2	8.46	308.8	0.867	0.028
15.3	14.2	35.2	0.998	0.954

From Table 3, it is concluded that the phase transfer at higher frequencies is much better than at lower frequencies. Note that, in this particular case, the lower-frequency phase error introduced is approximately a wavelength of the highest observing band planned for VSOP and Radioastron (22 GHz with a period of 45.4 psec). If the ionospheric delay fluctuates rapidly (ionospheric scintillation), the phase error introduced cannot be removed in the postreal-time cross-correlation process. The optimum coherence factor of 1.0 is reduced. Note that, at the higher pair of frequencies shown, almost optimum coherency is kept even for a scintillation index of 0.5. For the lower band, coherency is almost completely lost. The coherence factor is inversely proportional to the sensitivity [Eq. (3)] of the interferometer. When the coherence factor is 1, the sensitivity is equal to the rms noise. When the coherence factor is below 1, the sensitivity rises above the rms noise, a nonideal situation.

2. Carrier Recovery Phase Noise. At the space VLBI spacecraft receiver of the E–S radio link, as well as at the space VLBI Earth station's receiver, the carrier recovery process considered may be the result of any combination of the following modulation schemes: an unmodulated carrier, a spread spectrum phase modulation (BPSK), or a quadriphase modulation (QPSK).

It has been shown that the phase error variance for carrier recovery processes, σ^2_{rcvr}, may be expressed as a function of the symbol signal-to-noise ratio, $SSNR$, the phase lock loop (PLL) receiver closed-loop bandwidth, B_l, and the symbol period, T_s, as

$$\frac{\sigma^2_{rcvr}}{B_l T_s} = \frac{1}{SSNR} \tag{8}$$

for an unmodulated carrier, as

$$\frac{\sigma^2_{rcvr}}{B_l T_s} = \frac{1}{SSNR} + \frac{1}{SSNR^2} \tag{9}$$

for BPSK modulation, and as

$$\frac{\sigma^2_{rcvr}}{B_l T_s} = \frac{1}{SSNR} + \frac{9}{2SSNR^2} + \frac{6}{SSNR^3} + \frac{3}{2SSNR^4} \tag{10}$$

for QPSK modulation. For very strong SSNR, the three cases converge to $1/SSNR$.

3. Required Phase-Transfer Link Frequencies. In choosing the phase-transfer frequencies, it seems that the most important consideration should be given to the ionospheric propagation effects. Therefore, frequencies approximately 14 GHz or higher are the most suitable for phase transfers for space VLBI missions. Also, the uplink and downlink frequencies should be kept as close as possible.

D. Space VLBI System Characteristics

Table 2 is a summary of the salient radio link and orbital characteristics of Radioastron (Russia) and VSOP (Japan) [3,4,7].[3,4] These are space VLBI spacecraft to be launched in 1996. Many telemetry receiving stations spread around the Earth will be used. An example of these is the DSN orbiting VLBI subnet (United States), whose main characteristics are summarized in Table 4. A next-generation space VLBI mission being considered, the International VLBI Satellite (IVS), has also been included in Table 2 [5].

III. Interference Criteria

A. S–E Telemetering Link

A computer simulation was used to determine the cross-correlation SNR degradation versus the interference to the system noise ratio of the space VLBI Earth station. The VLBI Earth station is assumed to be interference free. Three types of interference were used: wideband noise, continuous-wave (CW) worst case (constant phase), and continuous-wave most-likely case (random phase). Figure 3 contains

[3] Ibid.

[4] D. W. Murphy, personal correspondence with D. Murphy, Jet Propulsion Laboratory, Pasadena, California, 1992.

the results of the simulation for the analog system and for the two-level (1-bit) and four-level (2-bit) quantization schemes. In all cases, the telemetry SSNR of the space VLBI Earth station was set to a baseline value (no interference) of $SSNR = 6$ dB.

Table 4. Summary of DSN space VLBI Earth station characteristics.

Parameter	X-band	Ku-band
Receive frequency tuning, GHz	8.025–8.5	14.0–15.35
−1-dB receive bandwidths, MHz	50	500
Receive zenith G/T, dB/K	33.7	37.3
Transmit frequency tuning, GHz	7.145–7.235	15.25–15.35
Transmit antenna gain, dB	54.7	61.0
Transmit power levels, W	5	0.5
−1-dB transmit bandwidths, MHz	50	100
Receive or transmit polarizations	RHCP or LHCP	RHCP or LHCP
Telemetry receiver capability, MB/sec	144	144
Antenna diameter, m	11	11

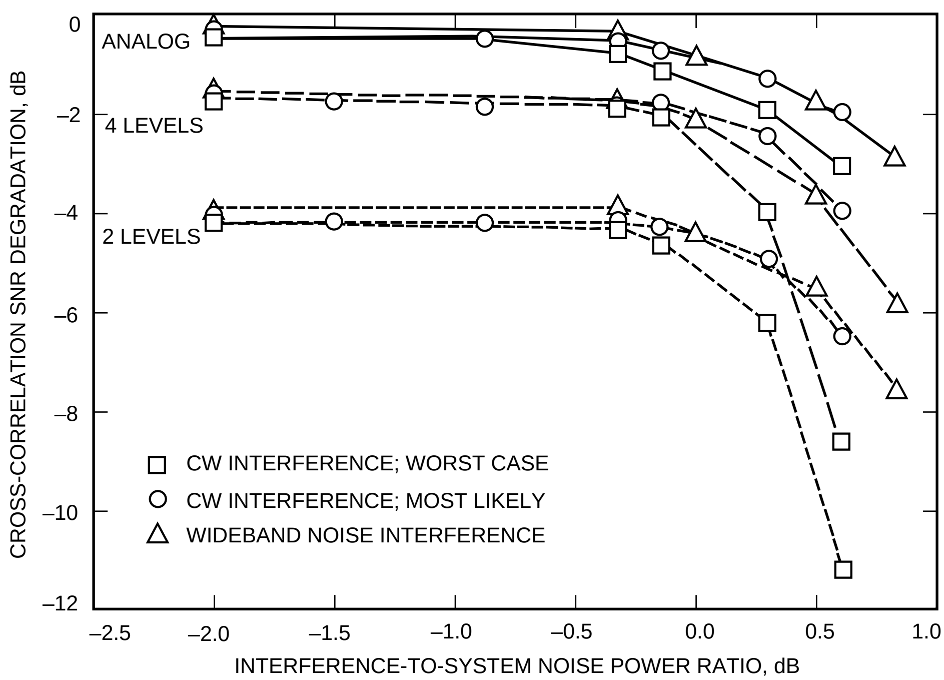

Fig. 3. Cross-correlation SNR degradation as a function of interference-to-system noise power ratio.

Protection criteria for telecommunication links for near-Earth research satellites [6] suggest that interference is harmful if the link threshold performance is decreased by more than 1 dB. From Fig. 3, the 1-dB degradation threshold for the three cases being considered may be set to a system noise power ratio to interference power, N/I, of approximately 0 dB. A typical system noise temperature for space VLBI Earth stations is 250 K. This corresponds to a system noise spectral density of −204 dB (W/Hz). Therefore, the maximum allowable interference power would be −204 dB (W/Hz).

B. Phase-Transfer Link

This link has been discussed in Sections II.A.2 and II.C. Phase errors are introduced primarily by the propagation medium at 8 GHz. A phase coherence error budget is contained in [7].

1. E–S Link. The system noise temperature of planned receiving systems on board space VLBI spacecraft is approximately 600 K. This corresponds to a system noise spectral density of −171 dB (W/kHz). Using the protection criteria of $N/I = 6$ db [6], the maximum allowable interference noise power, therefore, would be −177 dB (W/kHz). The satellite circuit random phase-noise estimation of 2.56-deg rms [7] would be increased to 3.2-deg rms by applying Eq. (8).

2. S–E Link. The system noise temperature of planned space VLBI Earth station receiving systems is approximately 250 K. This corresponds to a system noise spectral density of −204 dB (W/Hz). Using the protection criteria of $N/I = 6$ dB [6], the maximum allowable interference noise power would be −210 dB (W/Hz). The estimated space VLBI Earth station receiver phase-noise contribution, the receiver phase-lock-loop SNR [7], of 2.56-deg rms would be increased to 3.2-deg rms by applying Eq. (8).

C. Interference Criteria Summary

Maximum allowable interference power at the input terminals of the space VLBI Earth station receiver has been found to be −204 dB (W/Hz) for the telemetering link and −210 dB (W/Hz) for the phase-transfer link. Maximum allowable interference power at the input terminals of the space VLBI spacecraft receiver has been found to be −177 dB (W/kHz). According to the recommendations of [6], there should be maximum interferences of −216 dB (W/Hz) at the input terminals of the Earth station receiver and −177 dB (W/kHz) at the input terminals of the space research space station, for 0.1 percent of the time in both cases. Therefore, the levels recommended in [6] are suitable for the protection of planned space VLBI systems.

IV. Sharing and Protection Criteria of Space VLBI Services in Bands Near 8, 15, and 40 GHz

There are many radio services that use the same frequency bands that are planned for space VLBI. The frequency bands and the radio services that have allocations [8] are listed in Table 5. These frequency bands will be used for the VSOP and Radioastron missions. There are no current missions that plan to use the frequency bands shown in Table 6 and allocated to the space research services. These frequencies may be used for space VLBI in the future. The proposed IVS mission is used as an example of a space VLBI mission that may use the near–40 GHz band.

The space VLBI communications links are susceptible to interference from other radio services that use the same frequency bands. Also, the other radio services are susceptible to interference from the space VLBI communications links. Therefore, a compatibility study was performed on these frequency bands. No study of the 74- to 84-GHz band is presented at this time.

A. Methodology

The initial approach is to calculate a worst-case interference value. If the interference paths are line of sight, then it is assumed that the boresights of the transmitting and receiving antennas are aligned and there are minimum distances between the transmitter and receiver. If the interference paths are over a great circle, then the interference margin is set equal to 0 dB and the coordination distance between the interfering transmitter and the receiver is computed. Interference margin is defined as the difference between the interference criterion at a receiver and the computed level of interference at a receiver.

Table 5. Frequency bands for space VLBI.

Frequency band, GHz	Direction	Existing services
8.025–8.5	Space-to-Earth	Fixed Mobile Fixed satellite (E–S) Earth exploration satellite (EES) (S–E) Meteorological satellite (E–S) Space research (S–E) Radio location Space research
7.145–7.235	Earth-to-space	Fixed Mobile EES (passive) Space research (passive) Space operations (E–S) Space research (E–S)
14–15.35	Space-to-Earth	Fixed satellite (E–S) Radio navigation Space research Fixed Mobile Radio navigation satellite Radio astronomy Land mobile satellite (E–S) Space research (passive) EES (passive)
15.25–15.35	Earth-to-space	Fixed Mobile Space research Space research (passive) EES (passive)

Table 6. Frequency bands for future space VLBI.

Frequency band, GHz	Direction	Existing services
37–38	Space-to-Earth	Fixed Mobile Fixed satellite (S–E)
40–40.5	Earth-to-space	Fixed Fixed satellite (S–E) Mobile Mobile satellite (S–E)
74–84	Space-to-Earth	Fixed Mobile Fixed satellite (E–S) Amateur Amateur satellite Radio location Fixed satellite (S–E) Mobile satellite (S–E)

A more realistic representation of interference is made when the space VLBI spacecraft orbits are generated from the orbital characteristics planned (Table 2). Computer simulations of interference are performed for each of the worst cases for which the interference margin is less than zero.[5] Tables 7–19 are summaries of the computer simulations involving the different interference scenarios.

B. Sharing and Protection Summary

The worst-case interference scenario results shown in Tables 7–19 ("worst-case interference margin" column) indicate that, for line-of-sight paths, the interference margins are negative for nearly all cases. For great-circle interference paths, the coordination distances shown in Tables 7–19 are large in many cases. Therefore, assuming these worst-case conditions, band sharing between space VLBI and other services is difficult. However, when the most realistic approach of computing the interference levels as a function of orbital position of the space VLBI spacecraft is taken, the percentage of interfering time results shown in Tables 7–19 ("Time" column) indicates that space VLBI communication links are very compatible with other services. It should be noted that those interfering times that are different from zero happen at the space VLBI spacecraft perigee and that they can be eliminated by appropriate mission operations design, e.g., not pointing the space VLBI spacecraft antenna to the Earth while in closest approach. Therefore, it is recommended that space VLBI can share the frequency bands in Tables 5 and 6 with existing radio services. Careful coordination may be required in some cases.

V. Conclusions

The technical characteristics and telecommunications requirements for space VLBI have been provided. It has been shown that the use of high, closely spaced frequencies for the phase-transfer uplink and downlink produces lower ionospheric errors and larger VLBI coherence factors and that the protection criteria for near-Earth research satellite links [6] are sufficient to protect the space VLBI links.

A frequency-sharing analysis between space VLBI radio links and existing radio services has been performed. The analysis shows that the space VLBI links are compatible with these other services.

Table 7. Interference from Radioastron space VLBI phase reference downlink (8.025–8.5 GHz) to other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion	Orbit or location	Antenna and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	-150 dBW/m^2 in 4 kHz	Canberra	—	3	—	-46.6
Fixed satellite (E–S)	-138.6 dBW in 50 MHz	343.8 deg east	36.5 dBi, Earth center	0	—	-12.9
Earth-exploration satellite (S–E)	-214.0 dBW/Hz	500-km altitude, 35-deg inclination	55.5 dBi, EES spacecraft	0	—	-53.7
Meteorological satellite (E–S)	-189.9 dBW in 960 kHz	343.8 deg east	27.0 dBi, Earth center	10.7	—	-54.7
Radio location	-166 dBW in 3 MHz	51.7 deg south, 148.98 deg east	34.0 dBi, east horizon	0	—	-56.8

[5] D. F. Bishop, "Frequency Band Compatibility Between Space VLBI and Other Radio Services," JPL Interoffice Memorandum 3396-92-33 (internal document), Jet Propulsion Laboratory, Pasadena, California, June 10, 1992.

Table 8. Interference to Radioastron space VLBI phase reference Earth station receiver (8.025–8.5 GHz) from other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	−216.0	—	38 dBi, horizon	—	311	0.0
Fixed satellite (E–S)	−216.0	—	20.1 dBi, 3-deg elevation	—	225	0.0
Earth-exploration satellite (S–E)	−216.0	500-km altitude, 35-deg inclination	6 dBi, EES Earth station	0	—	−52.9
Meteorological satellite (E–S)	−216.0	—	21.9 dBi, 3-deg elevation	—	452	0.0
Radio location	−216.0	—	34.0 dBi, east horizon	—	481	0.0

Table 9. Interference from Radioastron space VLBI phase reference uplink (7.145–7.235 GHz) to other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	−150.4 in 4 kHz	—	38.0 dBi, horizon	—	531	0.0
Passive sensors	−158 in 400 MHz	500-km altitude, 35-deg inclination	34.5 dBi, Earth center	0.12	—	−90.7
Space operations (E–S)	−113.5 in 100 kHz	500-km altitude, 35-deg inclination	0 dBi	0	—	−11.7

Table 10. Interference to Radioastron space VLBI phase reference spacecraft receiver (7.145–7.235 GHz) from other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	−207.0	51.7 deg south, 163.8 deg east	38.0 dBi, east horizon	0	—	−31.7
Space operations (E–S)	−207.0	Canberra	49.5 dBi, space operations spacecraft	2	—	−100.2

Table 11. Interference from VSOP space VLBI downlink (14–15.35 GHz) to other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion	Orbit or location	Antenna and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed satellite (E–S)	−211.3 dBW/Hz	81 deg east	40.2 dBi, Earth center	0	—	−16.6
Radio navigation	−209.0 dBW/Hz	31.3 deg north, 261 deg east	50 dBi, east horizon	0	—	−48.2
Fixed and mobile	−148.0 dBW/m^2 in 4 kHz	Goldstone	—	6	—	−17.6
Radio navigation satellite	−136.0 dBW in 34 MHz	31.3 deg north, 261 deg east	0 dBi	0	—	−0.4
Radio astronomy	−221.0 dBW/m^2-Hz	30 deg north, 260 deg east	—	0	—	−54.6
Land mobile satellite (E–S)	−211.8 dBW/Hz	Geostationary, 81 deg east	33.0 dB, Earth center	0	—	−9.9
Passive sensors	−160.0 dBW in 200 MHz	500-km altitude, 35-deg inclination	41.8 dBi, Earth center	0	2.793×10^6	0.0

Table 12. Interference from Radioastron space VLBI downlink (14–15.35 GHz) to other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion	Orbit or location	Antenna and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed satellite (E–S)	−211.3 dBW/Hz	343 deg east	40.2 dBi, Earth center	0	—	−23.2
Radio navigation	−209.0 dBW/Hz	51.7 deg south, 148.98 deg east	50.0 dBi, east horizon	0	—	−50.1
Fixed and mobile	−148.0 dBW/m^2 in 4 kHz	38.47 deg south, 148.98 deg east	—	0	—	−19.5
Radio navigation satellite	−136 dBW in 34 MHz	51.7 deg south, 163.8 deg east	0 dBi	0	—	−2.2
Radio astronomy	−195.6 dBW/Hz	51.7 deg south, 163.8 deg east	27 m, zenith	0.02	—	−56.5
Land mobile satellite (E–S)	−211.8 dBW/Hz	Geostationary, 343.8 deg east	33.0 dBi, Earth center	0	—	−16.5
Passive sensors	−160.0 dBW in 200 MHz	500-km altitude, 35-deg inclination	41.8 dBi, Earth center	0	3.48×10^6	0.0

Table 13. Interference to space VLBI Earth station receiver (14–15.35 GHz) from other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed satellite (E–S)	−216.0	—	20.1 dBi, 3-deg elevation	—	172	0.0
Radio navigation	−216.0	—	0 dBi	—	65.9	0.0
Fixed and mobile	−216.0	—	35.0 dBi, horizon	—	268	0.0
Radio navigation satellite	−216.0	20,200-km altitude, 55-deg inclination	—	0	—	−32.0
Land mobile satellite (E–S)	−216.0		20.2 dBi, 3-deg elevation	—	216	0.0

Table 14. Interference from space VLBI Earth station (15.25–15.35 GHz) to other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	−156.0 in 4 kHz	—	35.0, horizon	—	341	0.0
Passive sensor	−160.0 in 200 MHz	500-km altitude, 35-deg inclination	41.0, toward 38.37 deg north 244.15 deg east	0	—	−88.9

Table 15. Interference to space VLBI spacecraft receiver (15.25–15.35 GHz) from other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	−207.0	31.3 deg north, 261 deg east	38.0 dBi, east horizon	0	—	−33.6

Table 16. Interference from IVS space VLBI spacecraft (37–38 GHz) to other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed satellite (E–S)	28.3 dB C/I	Geostationary, 210 deg east	36.5 dBi, Earth center	0	—	−22.5
Fixed and mobile	−203.0 dBW/Hz	38.47 deg south, 148.98 deg east	38.5 dBi, east horizon	0	—	−26.1
Fixed satellite (S–E)	−215.8 dBW/Hz	Canberra	58.4 dBi to geostationary at 148.98 deg east	0	—	−58.8

Table 17. Interference to IVS space VLBI Earth station receiver (37–38 GHz) from other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed satellite (E–S)	−216.0	—	14.5 dBi, 5–deg elevation	—	98	0.0
Fixed and mobile	−216.0	—	55 dBW EIRP, horizon	—	131	0.0
Fixed satellite (S–E)	−216.0	Geostationary, 148.98 deg east	36.5 dBi, Canberra	0	—	−66.6

Table 18. Interference from IVS space VLBI Earth station transmitter (39.5–40.5 GHz) to other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	−133	—	38.5 dBi, horizon	—	110	0.0
Fixed and mobile satellite (S–E)	−134.1	—	14.5 dBi, horizon	—	60	0.0

Table 19. Interference to IVS space VLBI spacecraft receiver (39.5–40.5 GHz) from other radio services.

Existing services	Service parameters			Interference results		
	Interference criterion, dBW/Hz	Orbit or location	Antenna gain and pointing	Time, percent	Coordination distance, km	Worst-case interference margin, dB
Fixed and mobile	−207	38.47 deg south, 148.98 deg east	55 dBW EIRP, horizon	0.023	—	−32.5
Fixed and mobile satellite (S–E)	−207	Geostationary, 210 deg east	36.5 dBi, Earth center	0	—	−27.9

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